Heavy-flavor production measurements in ATLAS

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For the ATLAS Collaboration

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ATLAS heavy-flavor hadron programs

Precision b-hadron decay measurement in search for new physics

- CP violation with $B_s \to J/\psi\phi$
- $B^0_{(s)} \to \mu^+\mu^-$ rare decays
- $B_s \to \mu^+\mu^-$ effective lifetime

Marek Biros
May 28, 2:15 PM, Para. #6

Nathan Barry Heatley
May 28, 11:15 AM, Plenary

Probing QCD with heavy-flavor hadrons

- Exotic hadrons
- $B_c^+ \to J/\psi D_s^{(*)+}$ decays
- Charmonium production

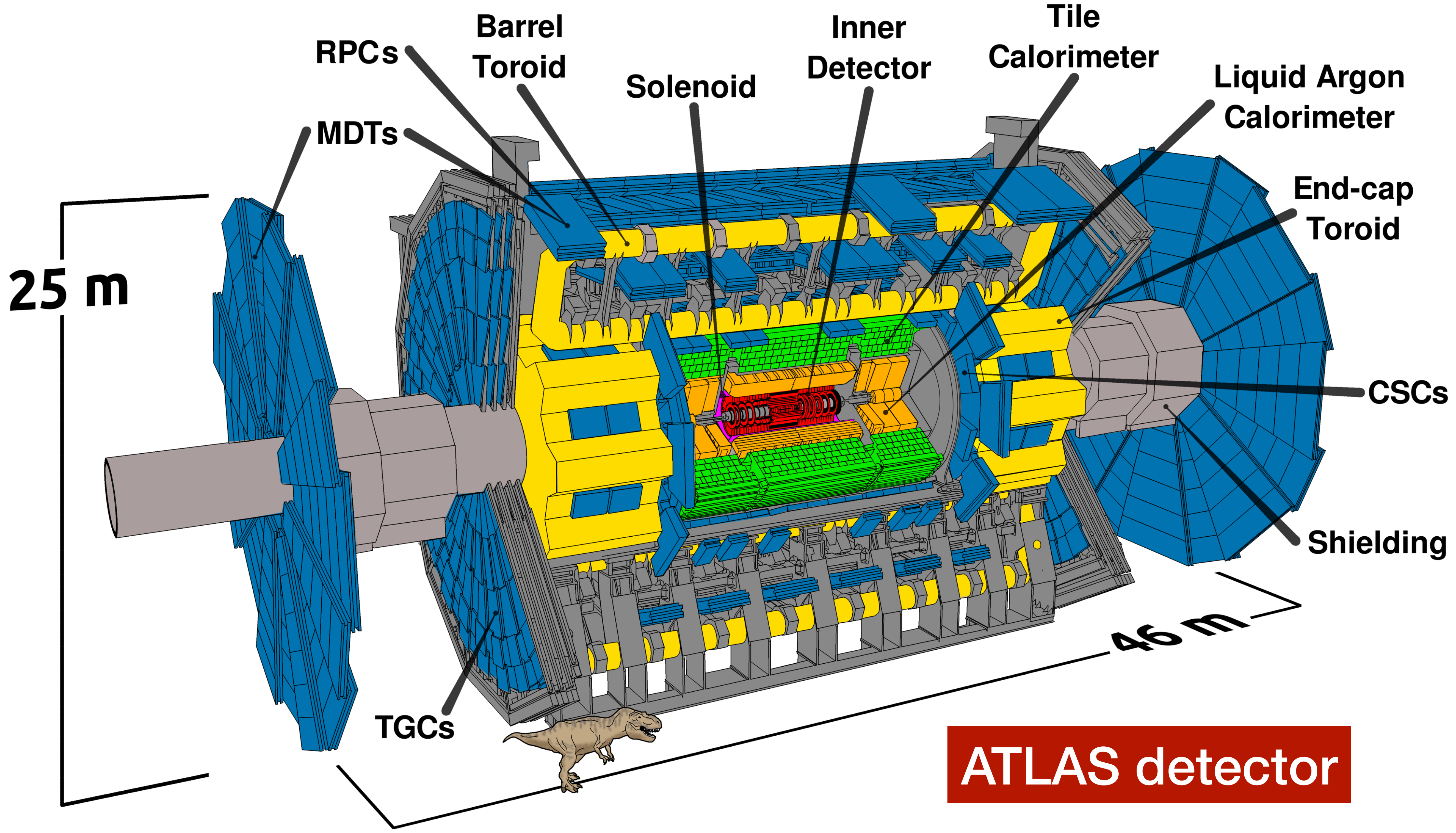
Probing properties of quark-gluon plasma

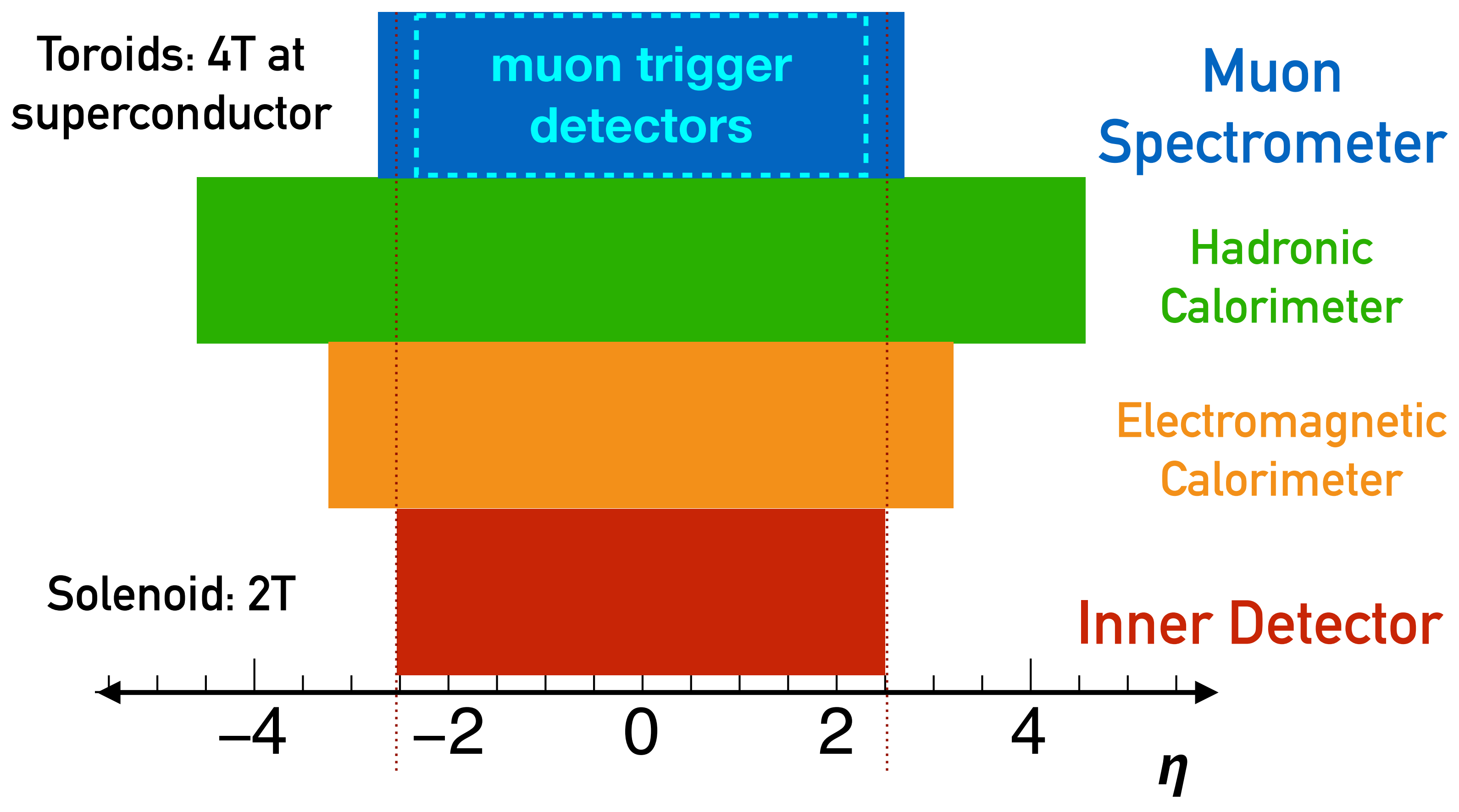
- Charmonium production in Pb+Pb
- Heavy flavor hadron production in Pb+Pb
- Heavy flavor hadron angular correlation in Pb+Pb

Covered in this talk

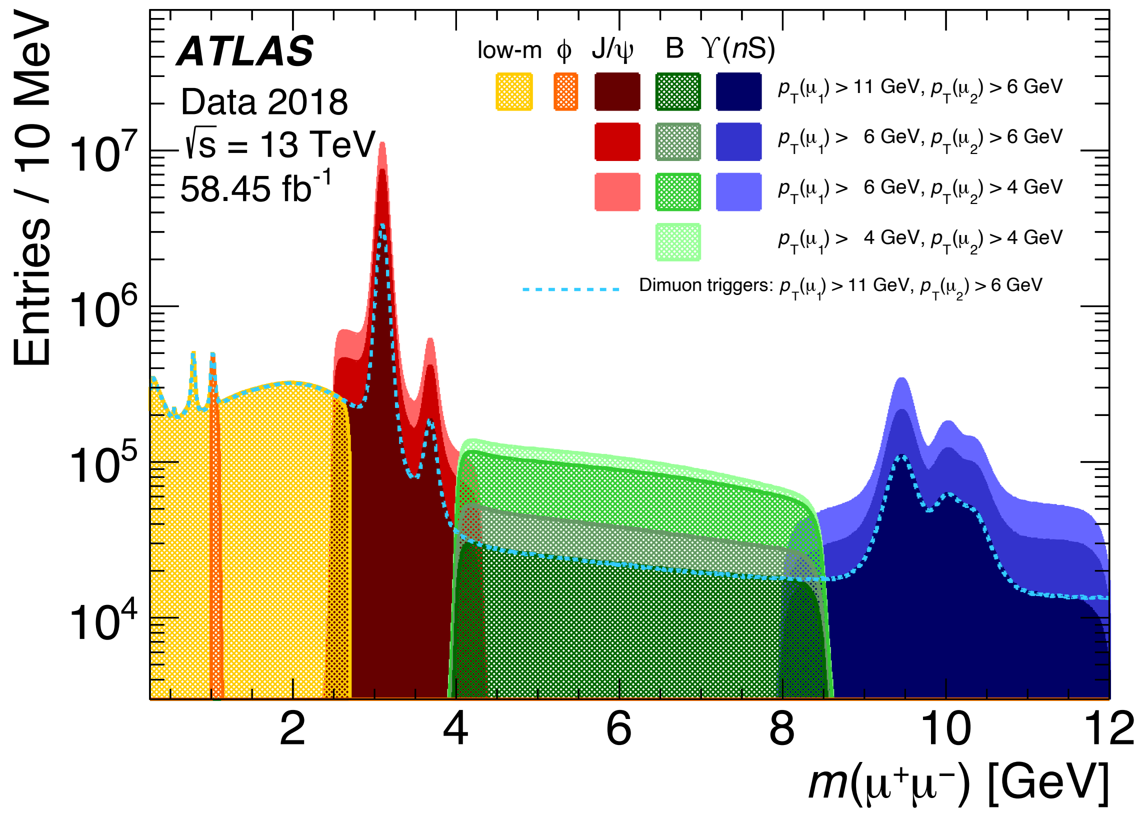
ATLAS flavor physics measurement summary submitted to Physics Reports: arXiv:2404.06829

ATLAS detector

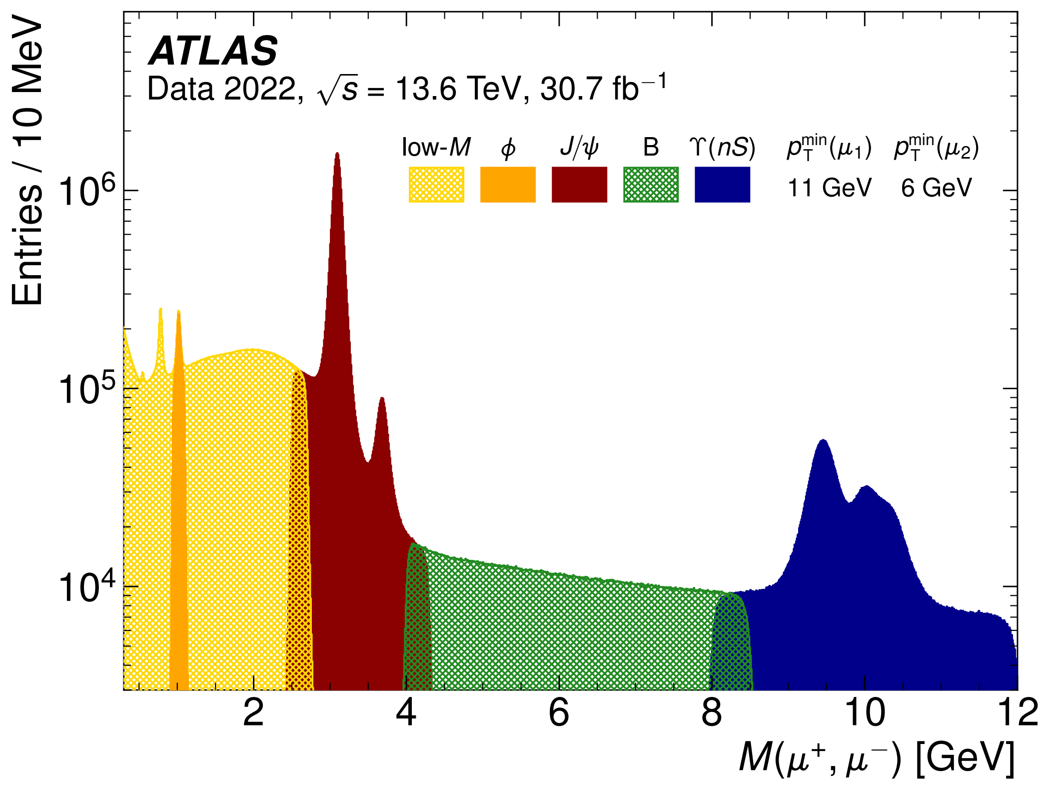




[JINST 15 (2020) P09015](#)



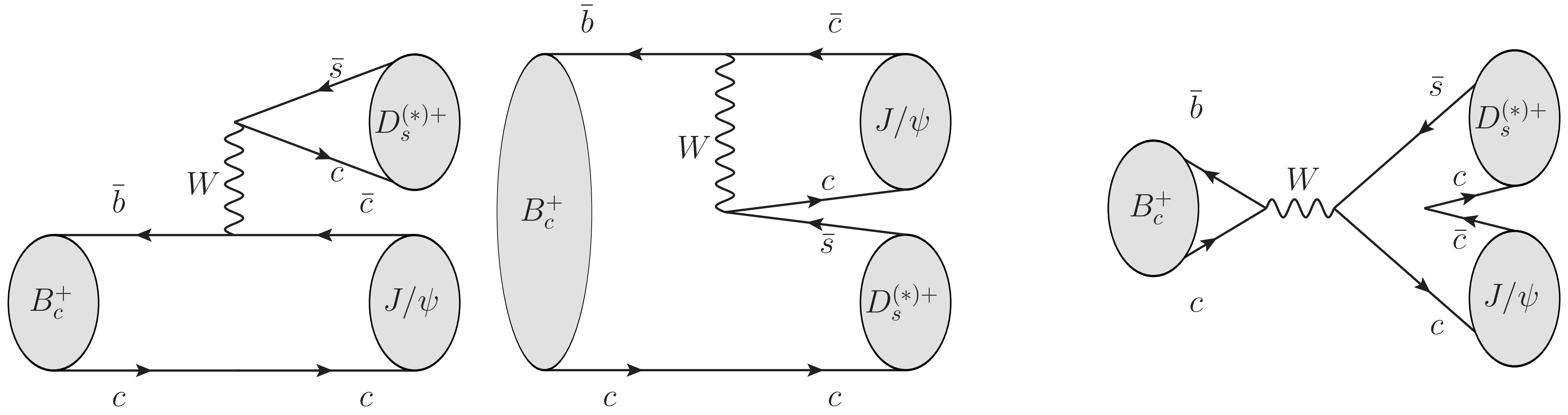
[arXiv:2401.06630](#)



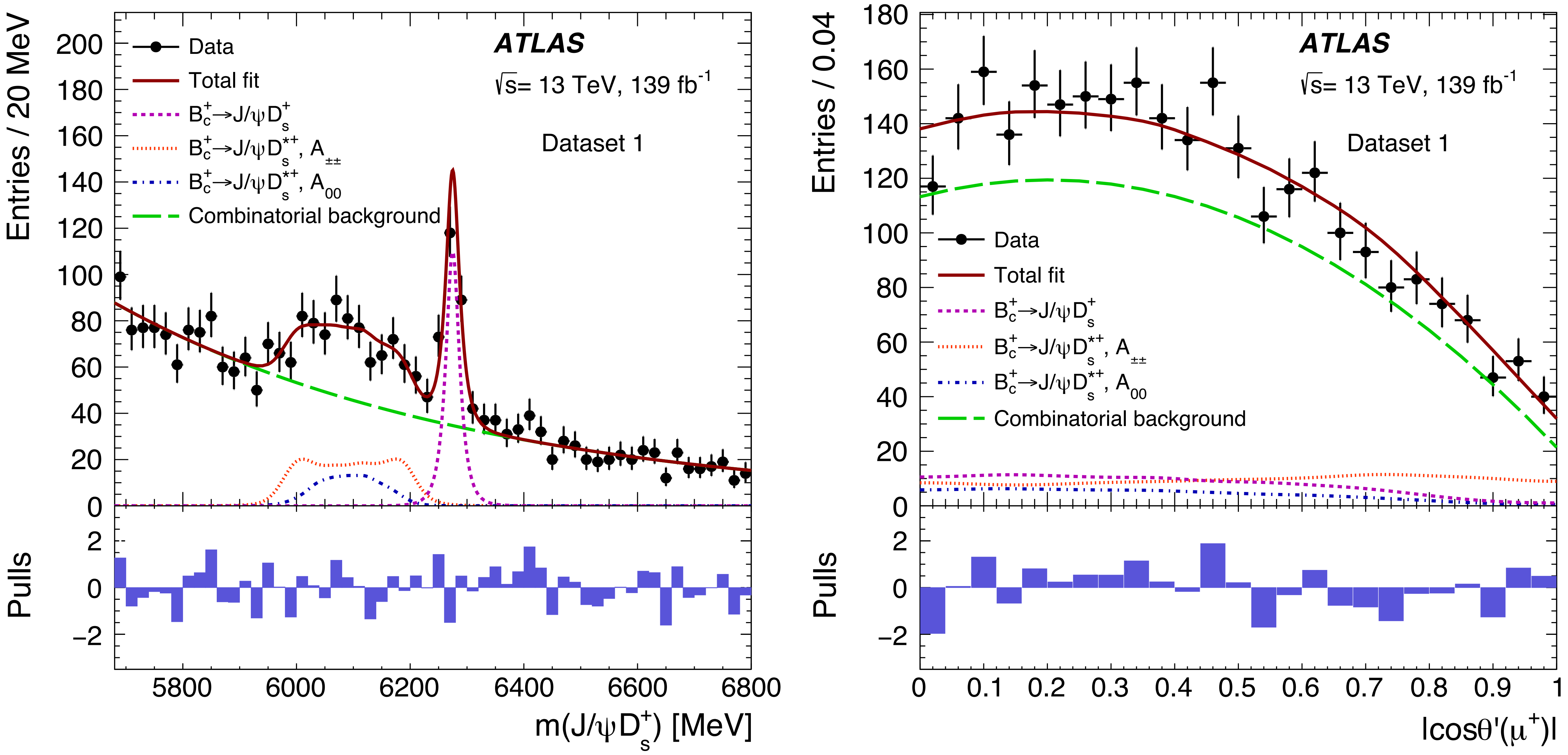
- ATLAS heavy-flavor hadron program primarily relies on single muon and dimuon triggers
- Lowest hardware-level trigger p_T threshold: 4 GeV

$B_c^+ \to J/\psi\, D_s^{(*)+}$ Analysis

- B_c^+ is a unique system with two heavy quarks: powerful probe to test different QCD calculation approaches for pp collisions
- $B_c^+ \to J/\psi\, D_s^+$ and $B_c^+ \to J/\psi\, D_s^{*+}$ decays observed by LHCb (*PRD 87 (2013) 112012*), and confirmed by ATLAS (*EPJC 76 (2016) 4*)
- The decay has contributions from:



- Repeat with full LHC Run2 data of 140 fb^{-1} (*JHEP 08 (2022) 087*)



- $D_s^+ \to \phi\pi^+$, $D_s^{*+} \to D_s^+\gamma$ or $D_s^+\pi^0$ (not reconstructed)
- Also analyzed reference channel of $B_c^+ \to J/\psi\, \pi^+$
- Fraction of transverse polarization ($A_{\pm\pm}$) of $B_c^+ \to J/\psi\, D_s^{*+}$ is extracted from $m(J/\psi D_s^+)$ and muon helicity angular distribution

$B_c^+ \to J/\psi\, D_s^{(*)+}$ branching fractions

[JHEP 08 (2022) 087](#)

Relativistic potential model (**PM**)

QCD sum rules (**SR**)

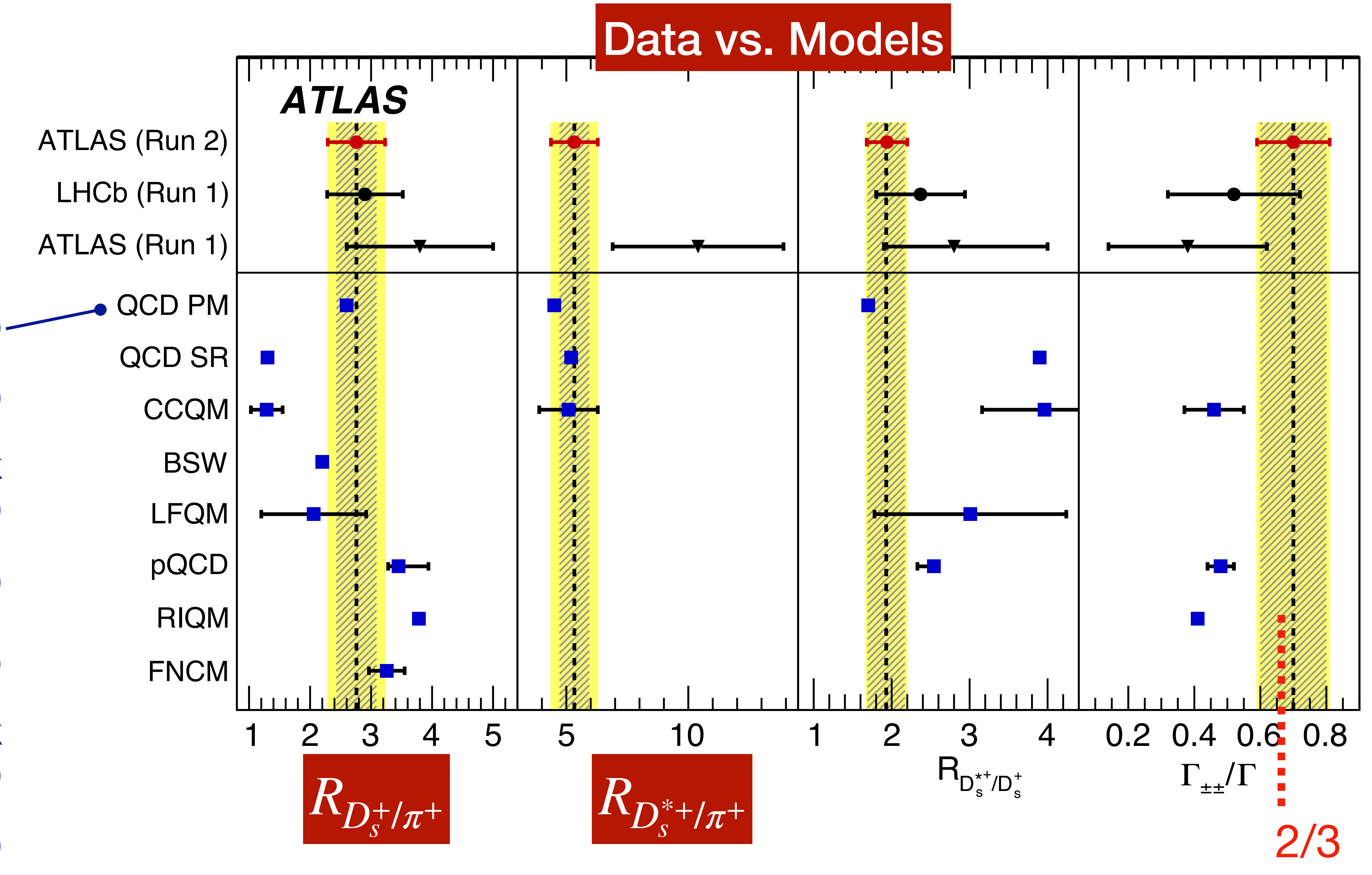
Covariant confined quark model (**CCQM**)

Bauer-Stech-Wirbel (**BSW**)

Light-front quark model (**LFQM**)

Relativistic independent quark model (**RIQM**)

QCD factorization (**FNCM**)



$$R_{D_s^+/\pi^+} = \mathscr{B}(B_c^+ \to J/\psi\, D_s^+)/\mathscr{B}(B_c^+ \to J/\psi \pi^+)$$

$$R_{D_s^{*+}/\pi^+} = \mathscr{B}(B_c^+ \to J/\psi\, D_s^{*+})/\mathscr{B}(B_c^+ \to J/\psi \pi^+)$$

Branching fraction ratios:

- Improved precision compared to Run1 results
- QCD relativistic potential model (**PM**) describes the data best

Transverse polarization fraction:

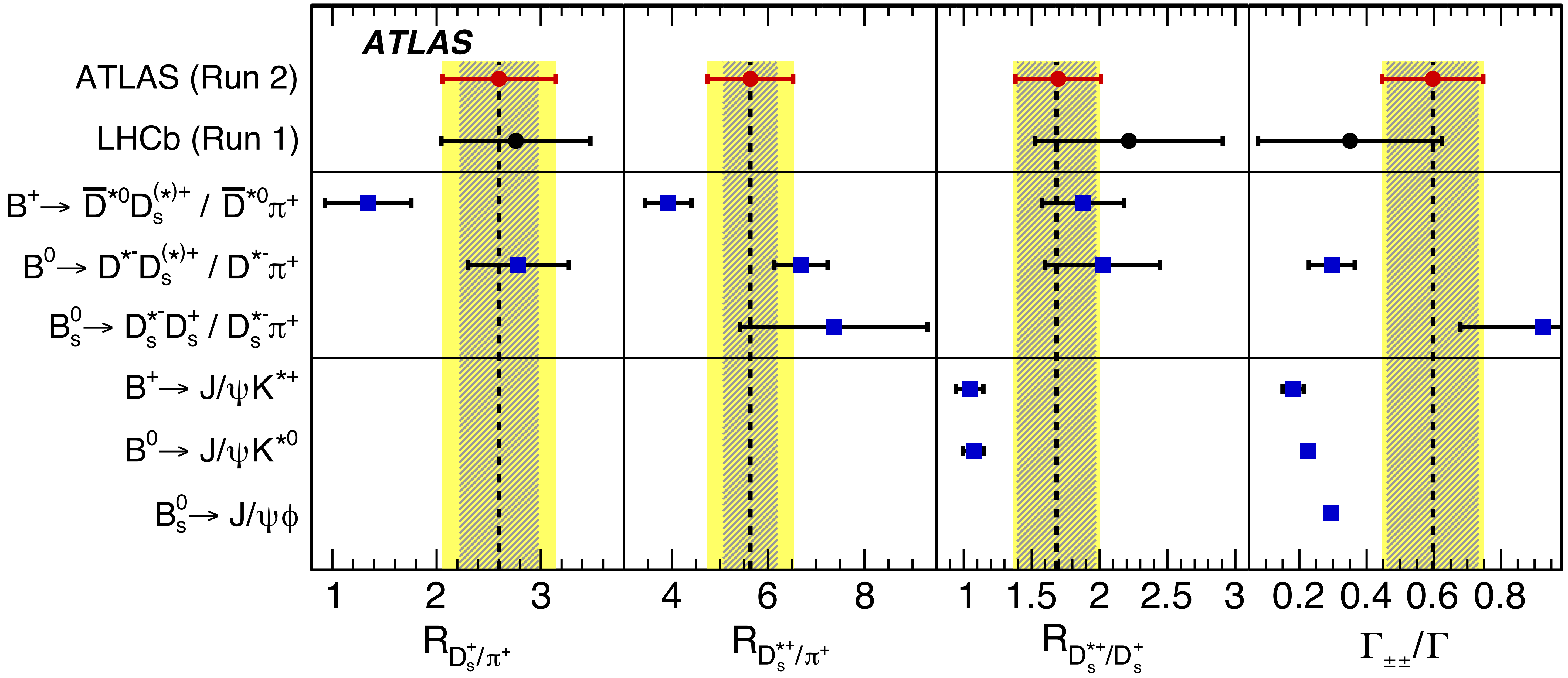
- Data consist with naive spin-counting of 2/3
- Model predictions are below 0.5

$B_c^+ \to J/\psi\, D_s^{(*)+}$ Results

B_c^+: [JHEP 08 (2022) 087]

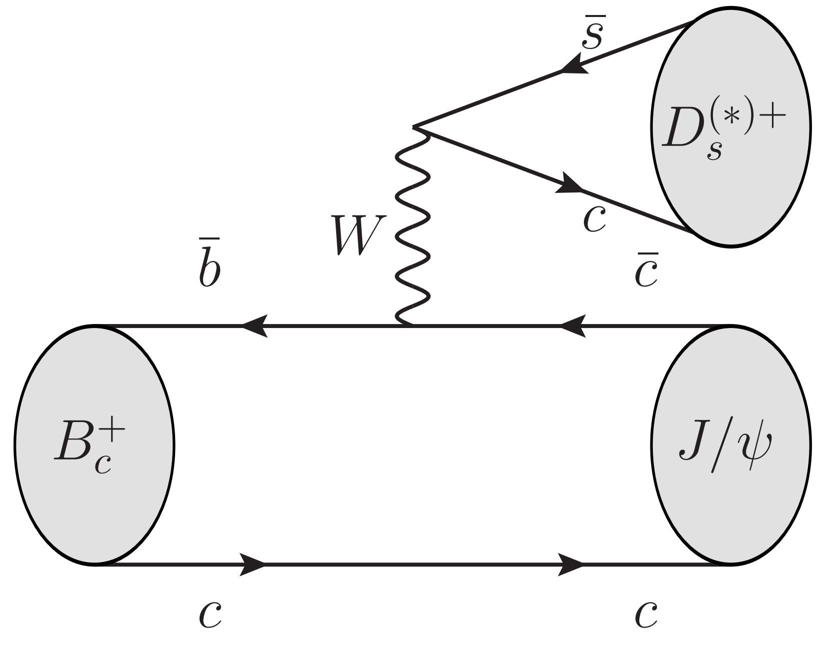
B^+, B^0, B_s^0: PDG [PTEP 2020 (2020) 083C01]

B_c^+ vs. B^+, B^0, B_s^0



Color-favored

Color-suppressed

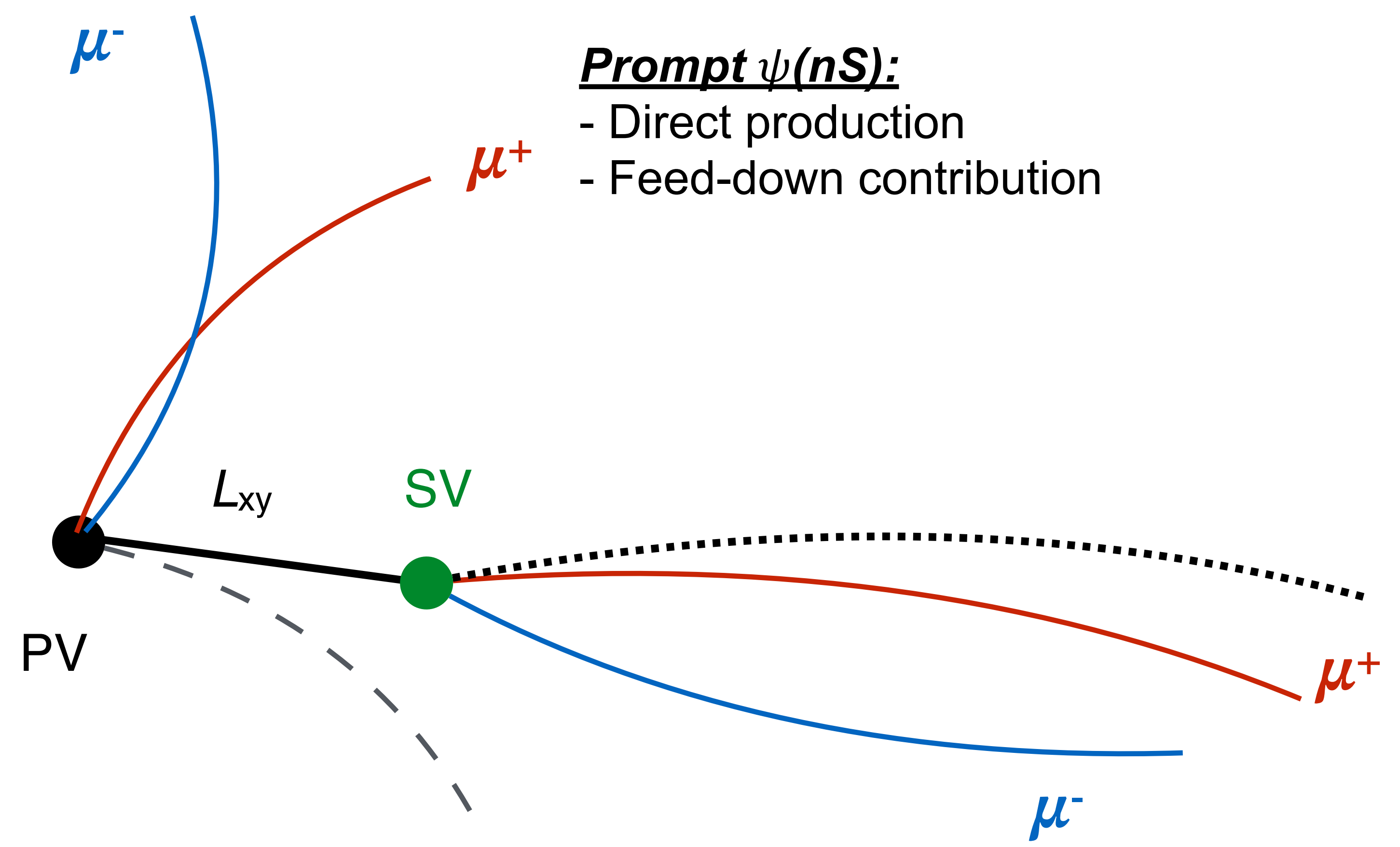


- Color-flavored tree diagram likely dominates the $B_c^+ \to J/\psi\, D_s^{(*)+}$ decay amplitudes

Charmonium production in pp

EPJC 84 (2024) 169

- Quarkonium production in hadronic collisions is still puzzling even 50 years after its discovery: yield vs. polarization
- Measured charmonia at LHC:
  - Prompt charmonia from direct QCD processes including feed-down
  - Non-prompt charmonia from decays of *b*-hadrons
- Same methodology used before in 5.02, 7, 8 TeV pp collision data

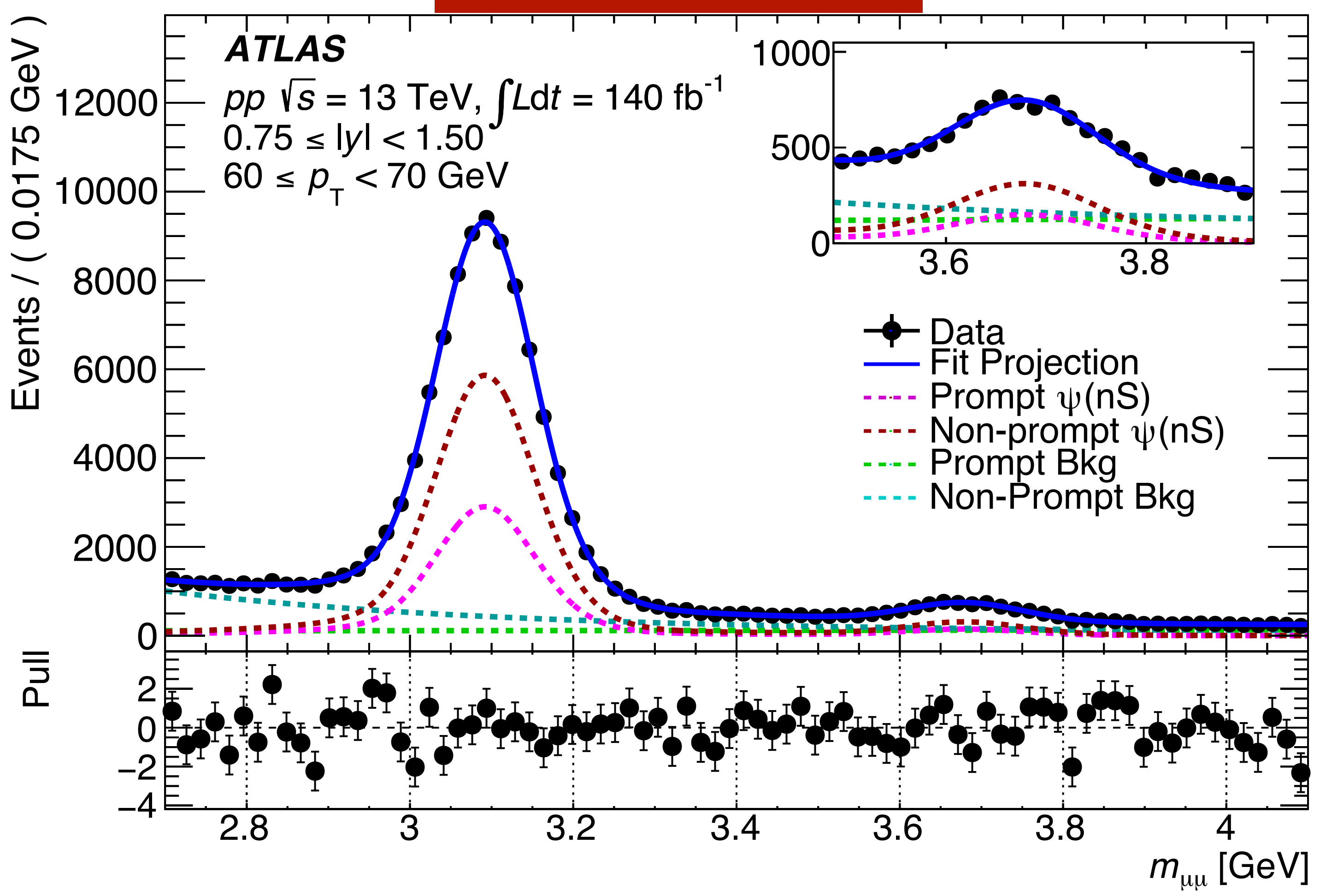


Non-prompt $\psi(nS)$:
- Decays from B hadrons

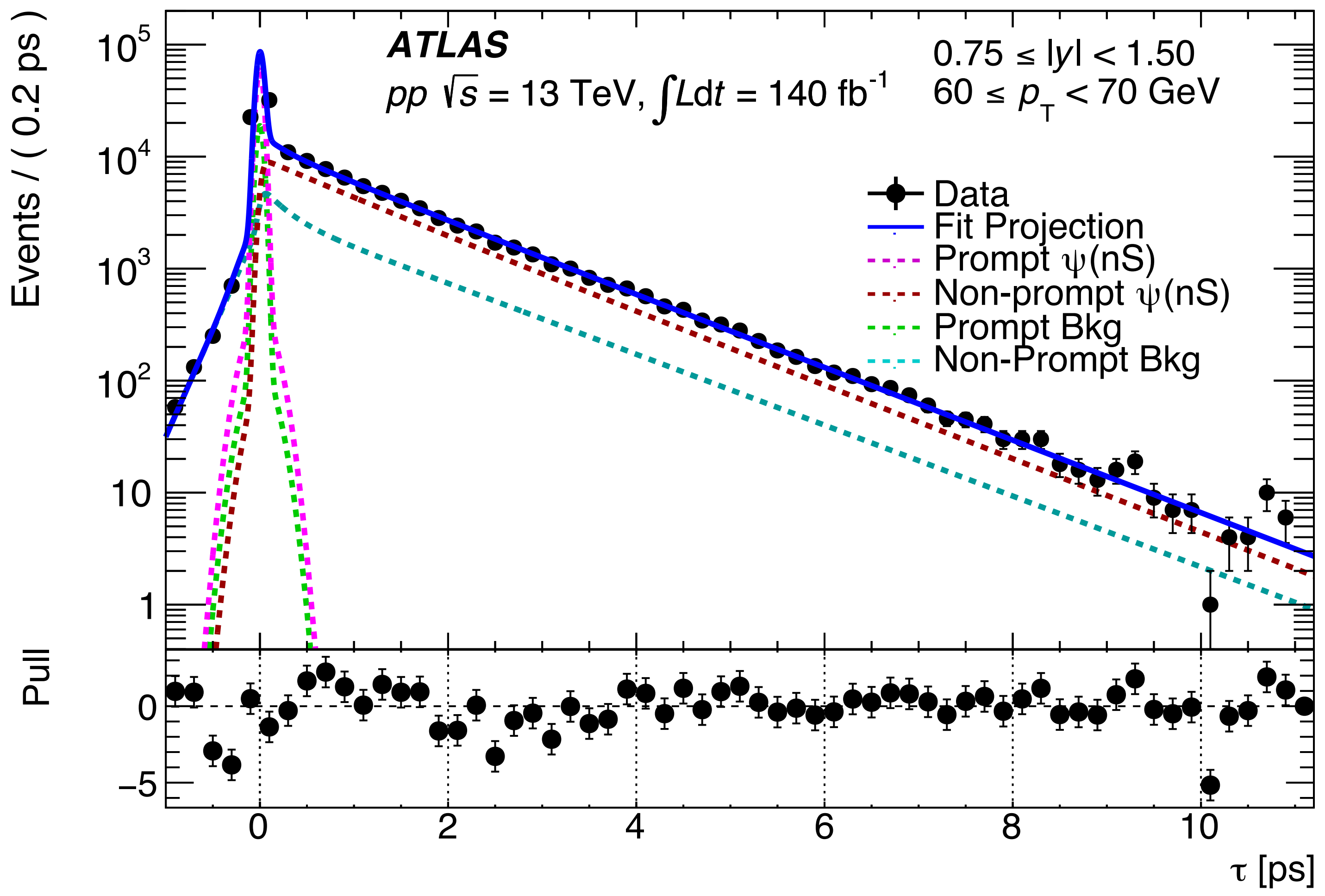
pseudo-proper lifetime:

$$\tau = \frac{L_{xy} m_{\mu\mu}}{p_{\mathrm{T}}^{\mu\mu}}$$

Dimuon mass



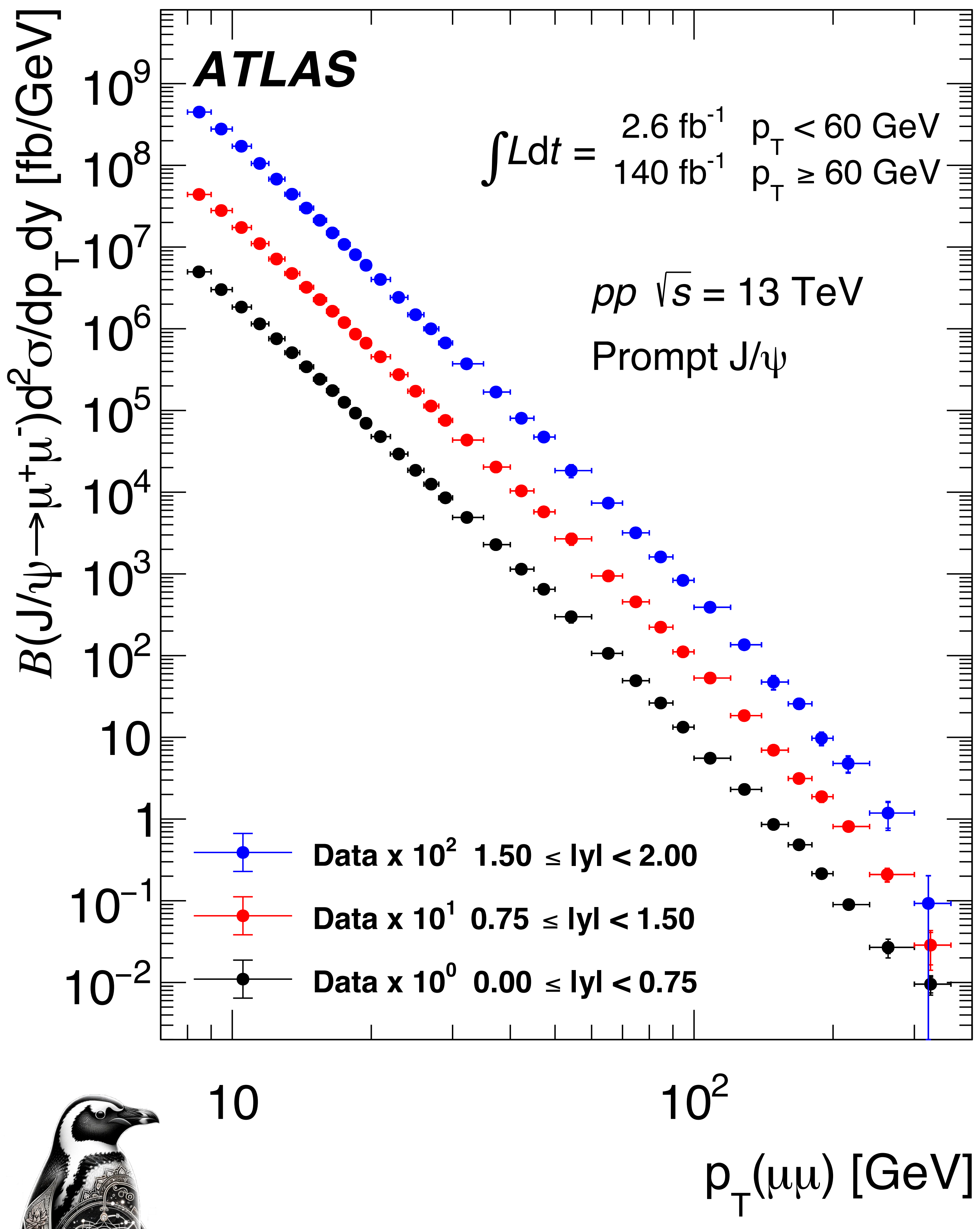
Dimuon pseudo-proper lifetime



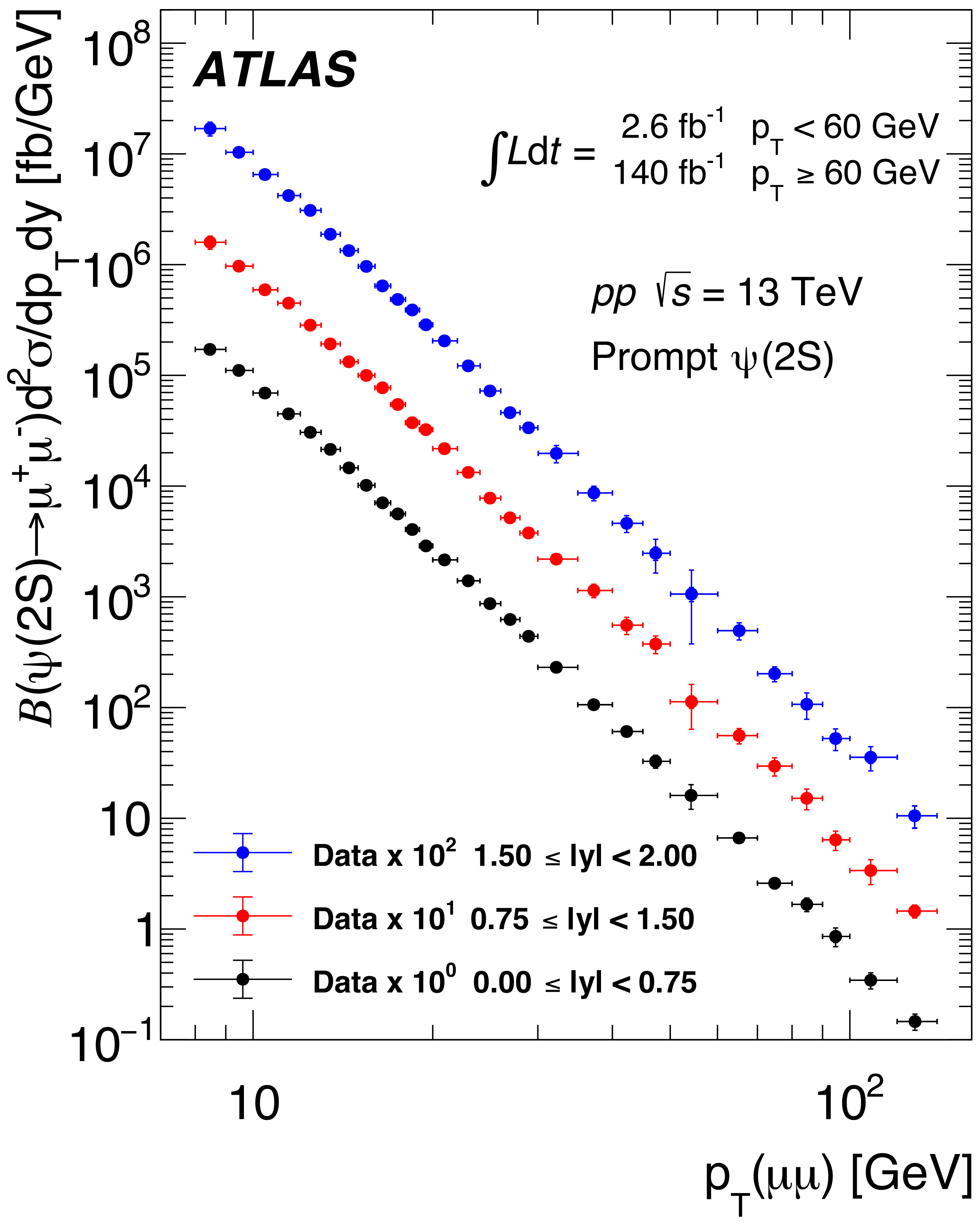
Prompt charmonium production

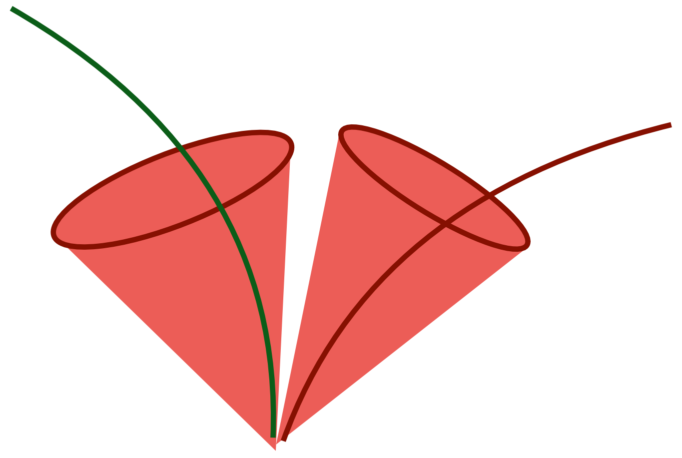
EPJC 84 (2024) 169

Prompt J/ψ



Prompt $\psi(2S)$





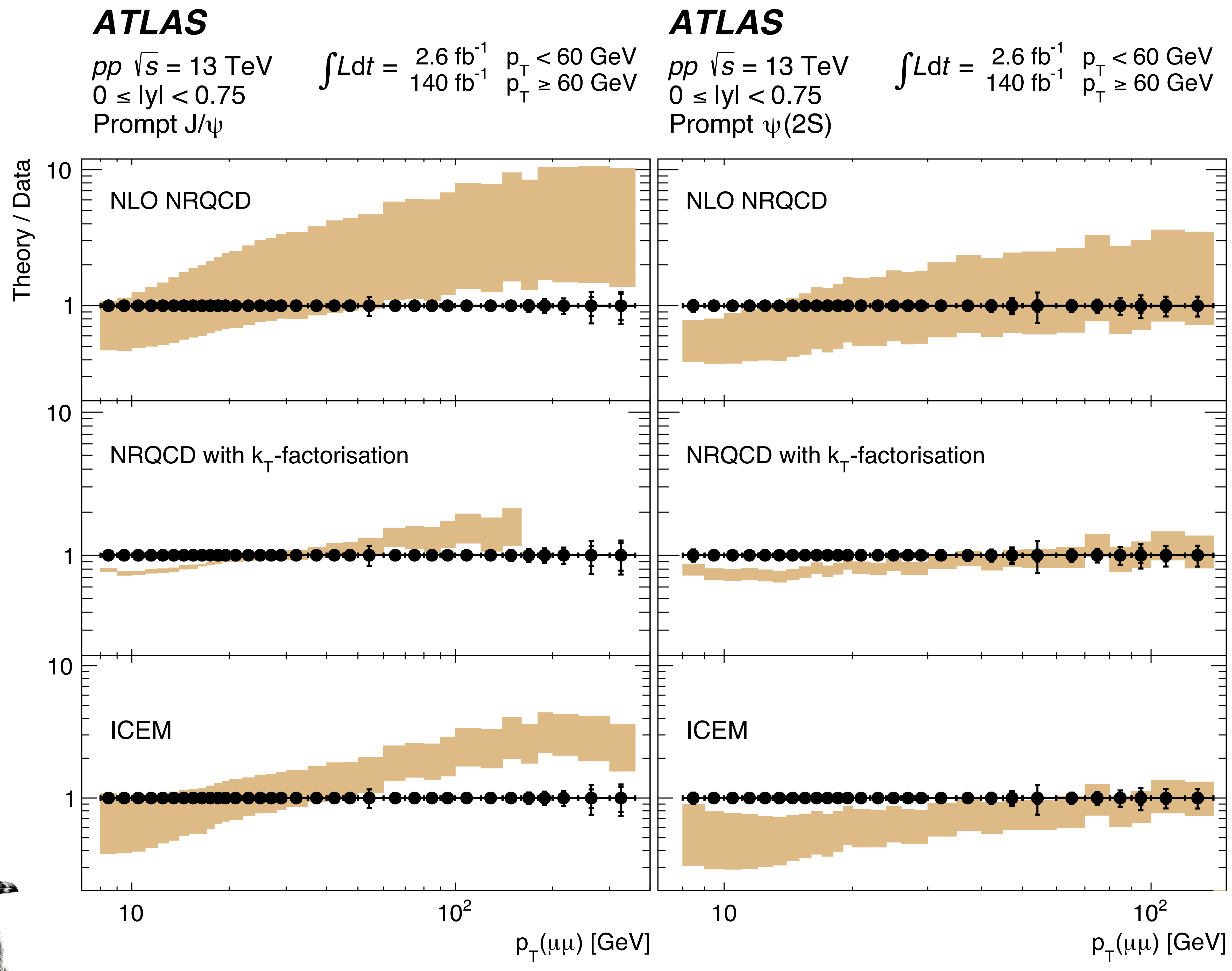
Hardware area-based online muon finding

- New results using 13 TeV Run2 data:
  - 2.6 fb^{-1} for $8 < p_T < 60$ GeV, dimuon trigger
  - 140 fb^{-1} for $p_T \geq 60$ GeV, single muon trigger
- p_T range: widest kinematic reach to date
  - $8 < p_T < 360$ GeV for J/ψ
  - $8 < p_T < 140$ GeV for ψ (2S)

Prompt charmonium data vs. models

EPJC 84 (2024) 169

Data vs. Models: Theory / Data ratio



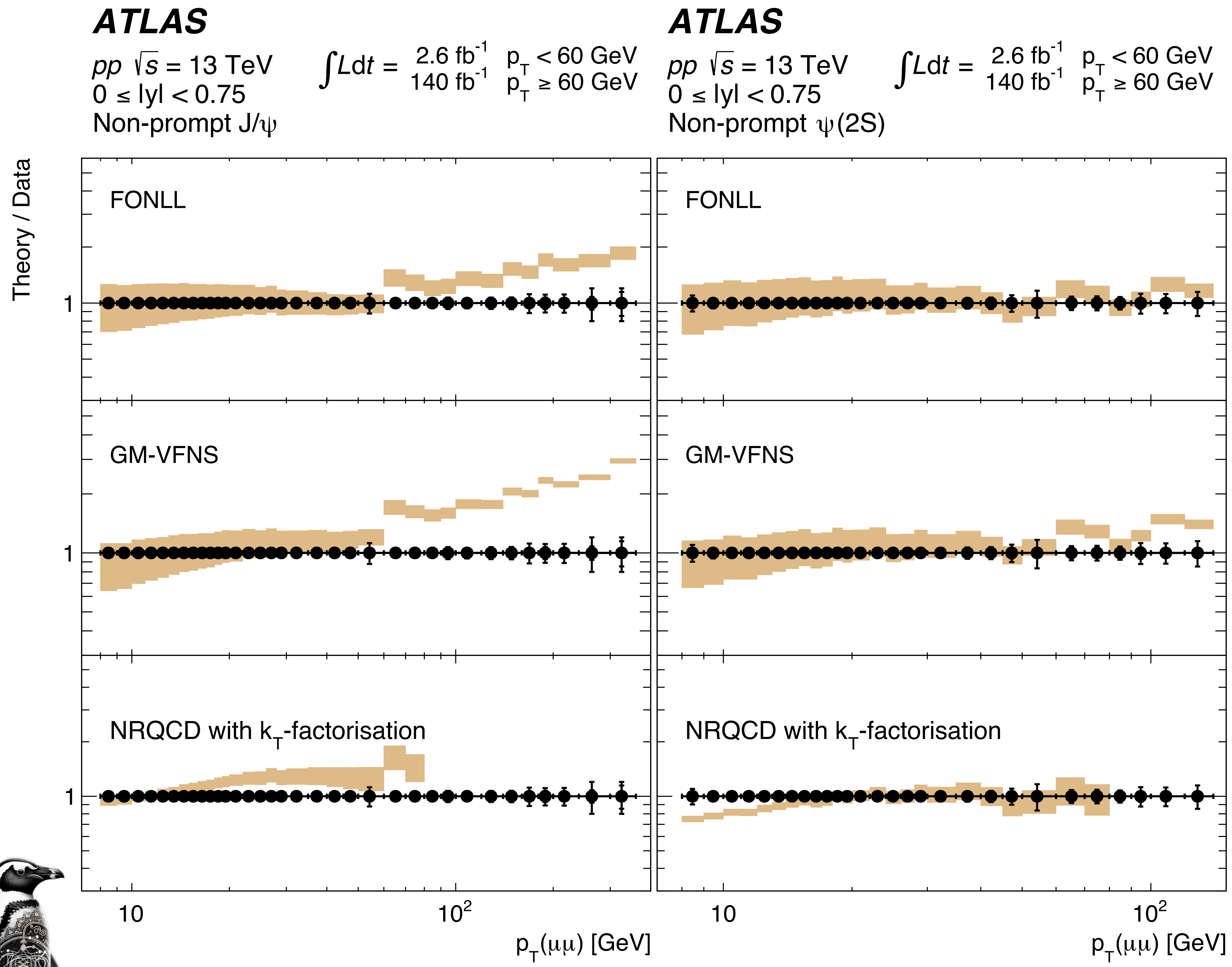
- NLO NRQCD
- NRQCD k_T-factorization
- Improved CEM

- Models tend to underestimate the production at low p_T production and overestimate the production at high p_T

Non-prompt charmonium production

EPJC 84 (2024) 169

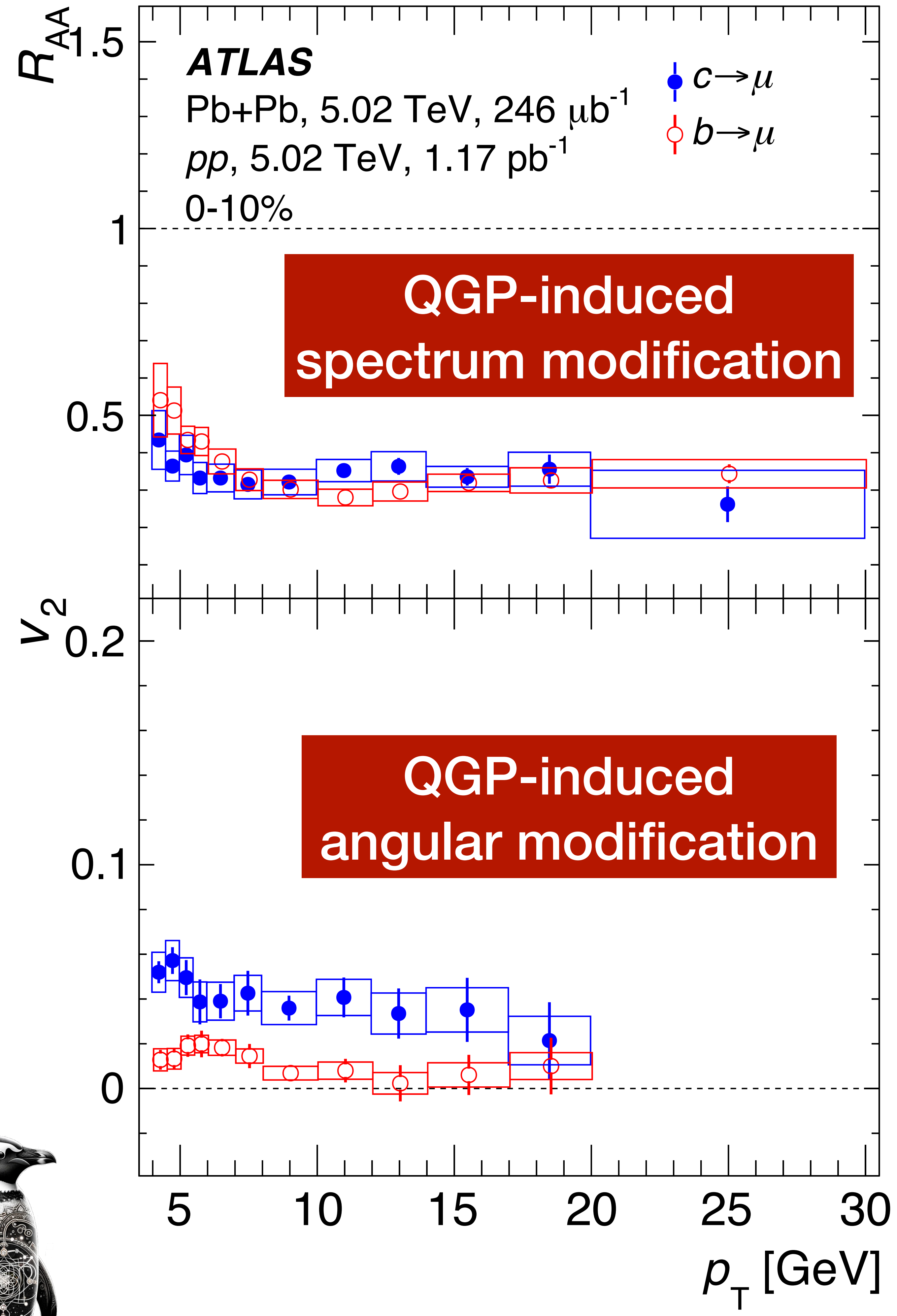
Data vs. Models: Theory / Data ratio



- FONLL
- General-mass-variable-flavor-number: GM-VFNS
- NRQCD k_T-factorization

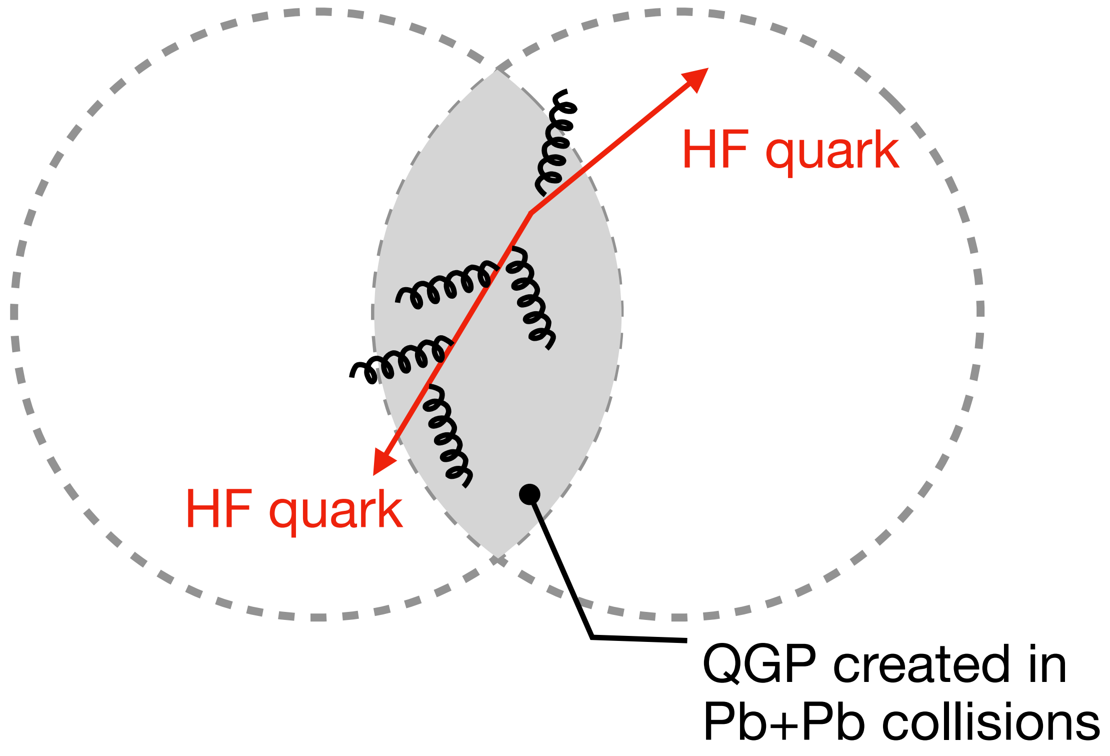
- Models can describe low p_T data, but overestimate the production at high p_T

Heavy-flavor in heavy ion collisions



PLB 829 (2022) 137077

$$R_{AA} = \frac{\text{per-NN yields in A-A}}{\text{yields in } pp}$$

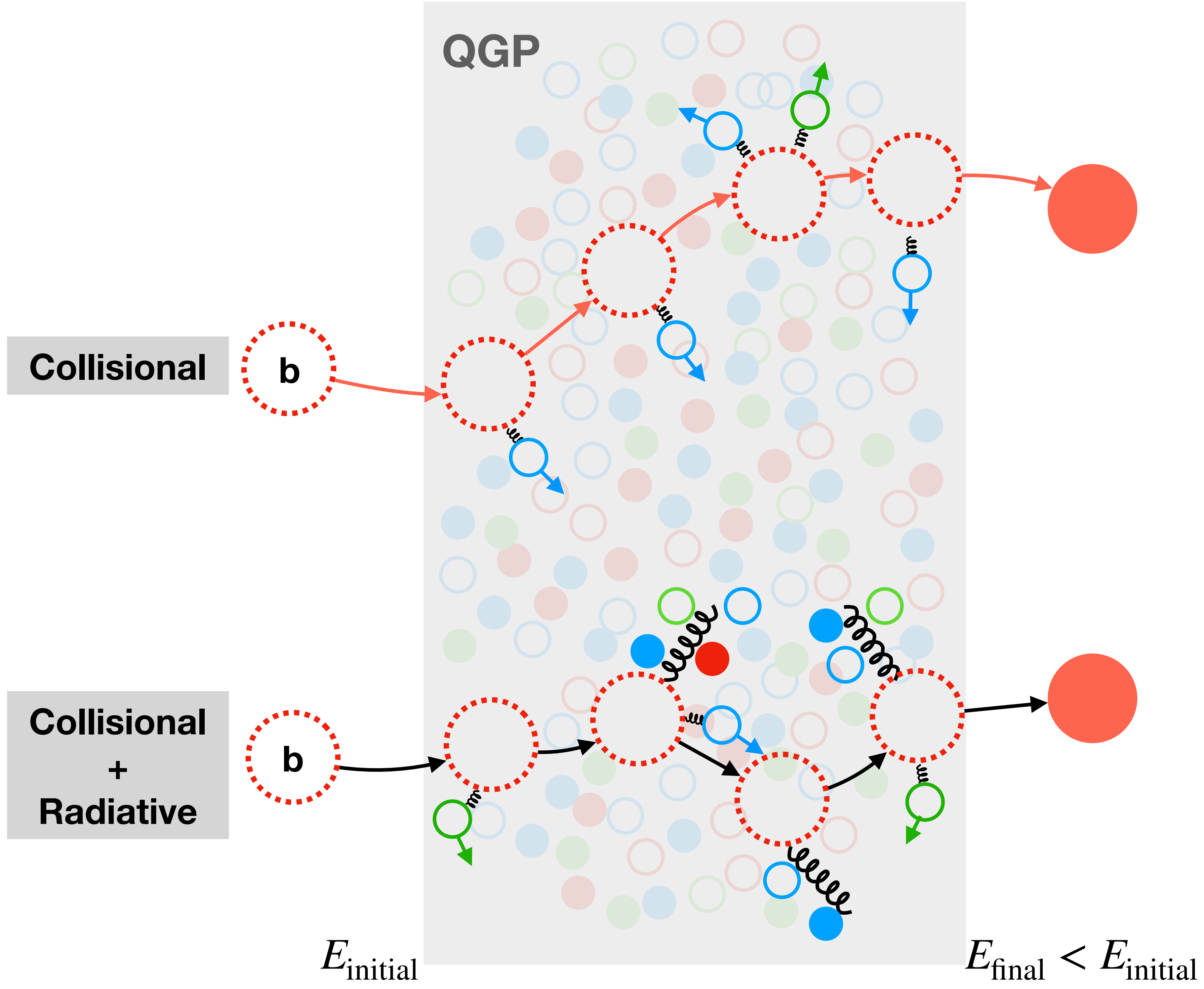


$$\frac{dN}{d\phi} \propto 1 + 2v_2\cos(\phi - \Psi_2)$$

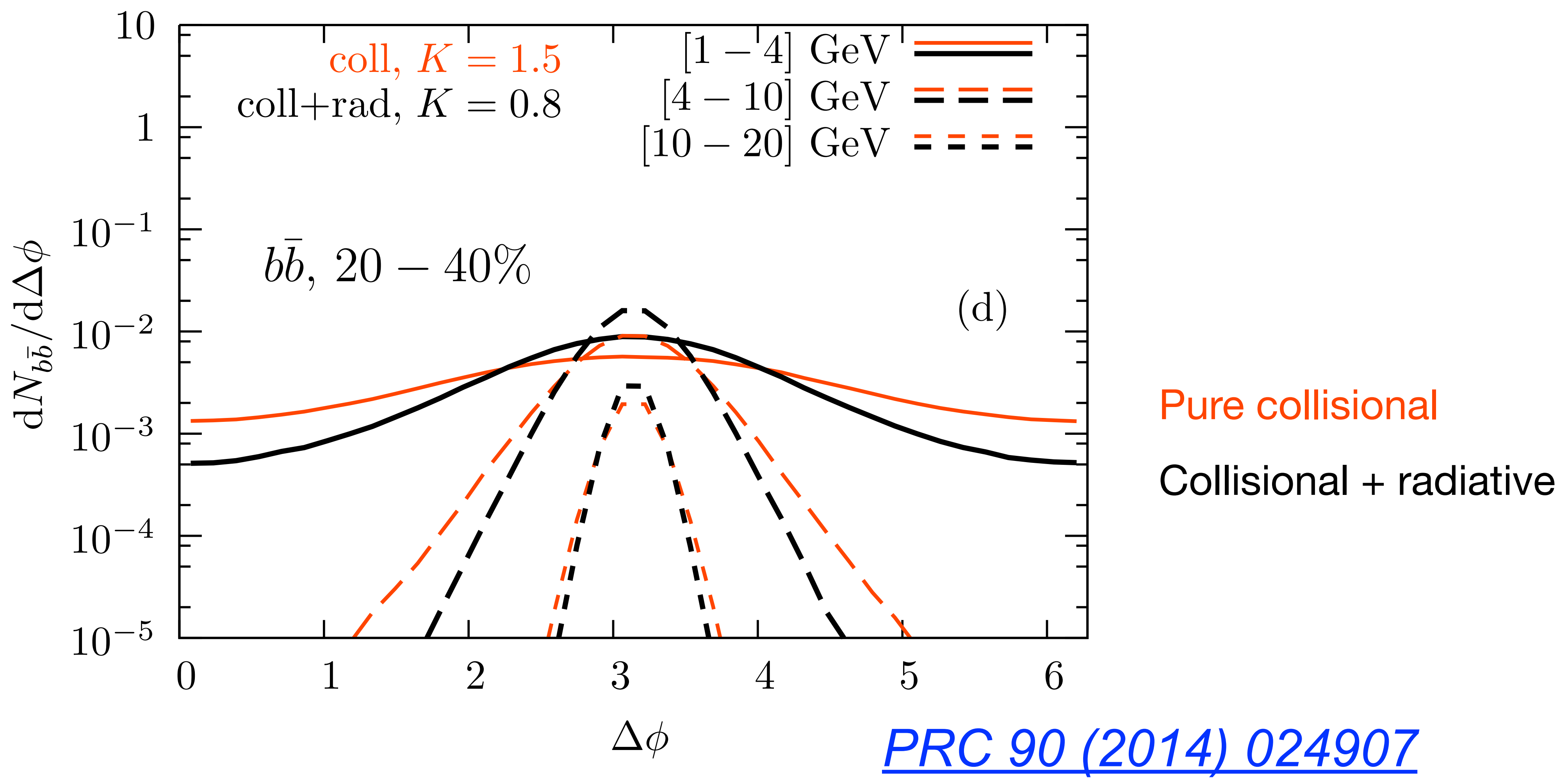
PLB 807 (2020) 135595

- Charm and bottom quarks are *produced early* in Pb+Pb collisions, and are sensitive probe to quark-gluon plasma (QGP) induced interactions
- Both HF spectra and angular distributions are strongly modified in heavy ion collision
- HF interacts with QGP strongly and loses energy

Heavy-flavor energy loss in QGP



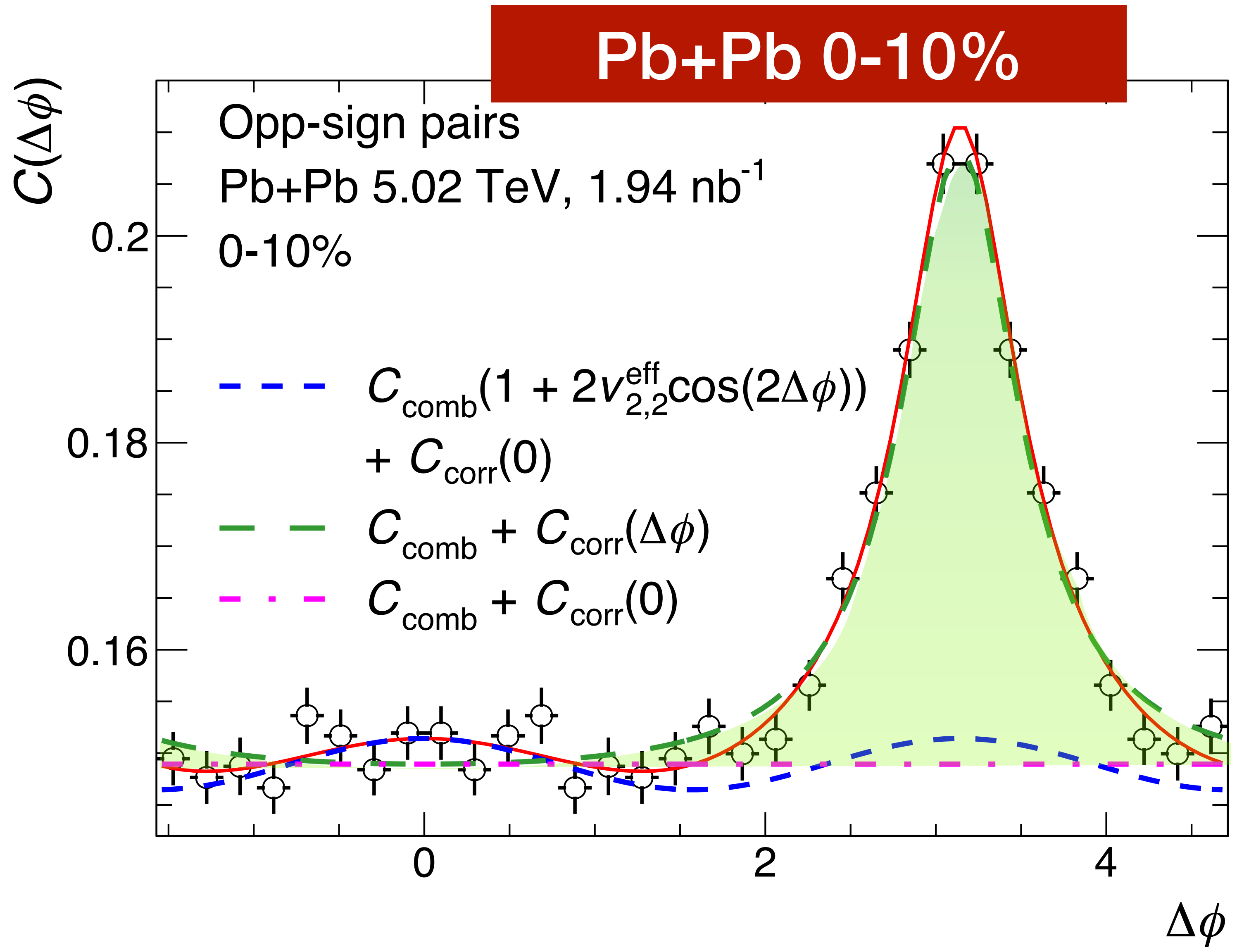
- Energy loss: collisional E_{loss} vs. radiative E_{loss}
- At fixed E_{loss}, pure collisional interaction leads to a broader $\Delta\phi$ correlation between $c\bar{c}$ and $b\bar{b}$
- One of the easiest ways to probe the $\Delta\phi$ correlation is to measure $\Delta\phi(\mu,\mu)$ between muons from HF decays

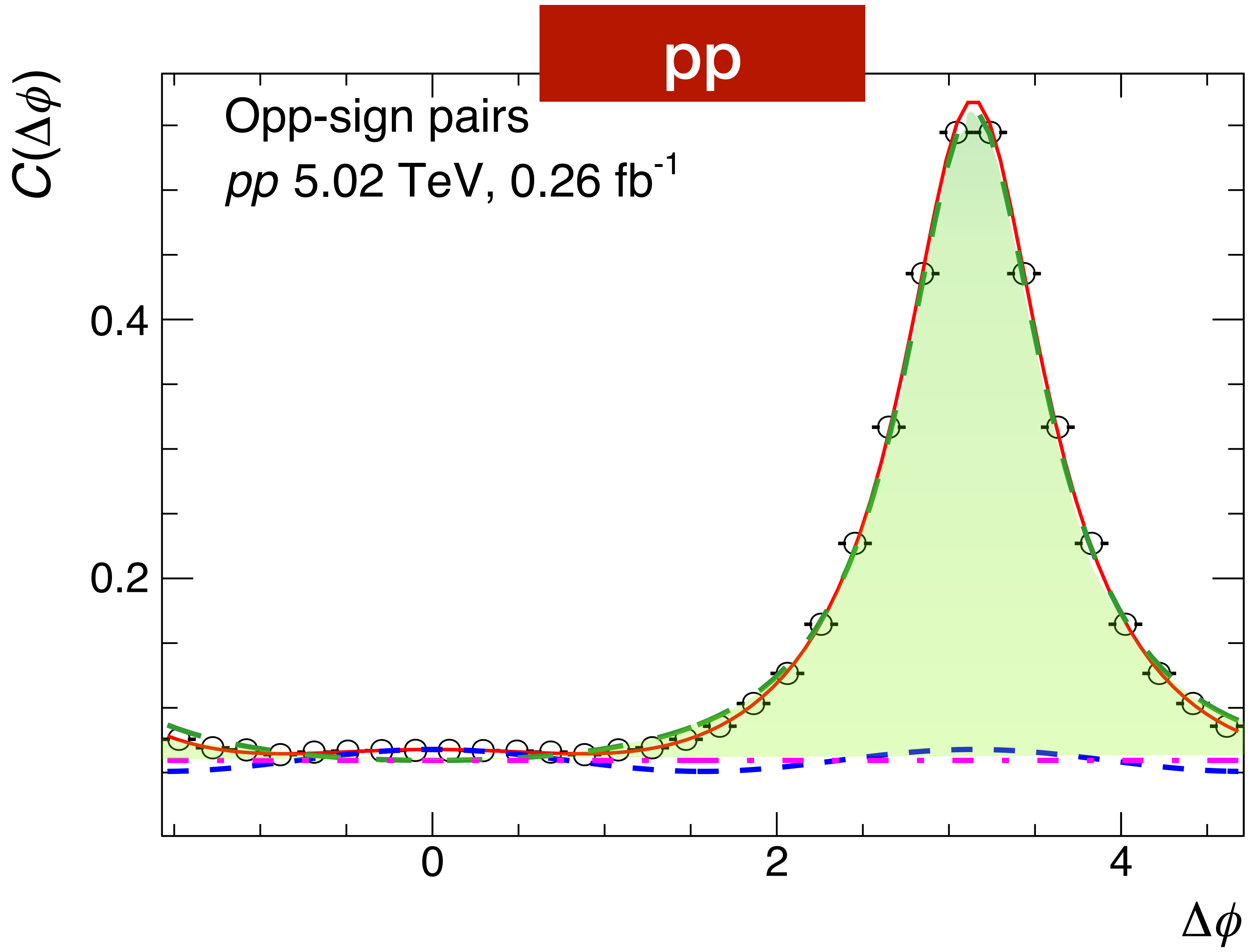


PRC 90 (2014) 024907

Heavy-flavor muon pairs in Pb+Pb

PRL 132 (2024) 202301





- HF muon pair correlation measured in 2015 and 2018 Pb+Pb data
- Back-to-back correlation width, Cauchy-Lorentz $\boldsymbol{\Gamma}$ or std deviation $\boldsymbol{\sigma}$, are extracted
- Separately for same-sign ($b\bar{b} \to \mu^{\pm}\mu^{\pm}$) and opposite-sign ($c\bar{c}/b\bar{b} \to \mu^{\pm}\mu^{\mp}$) muon pairs

$$C^{\rm Fit}(\Delta\phi) = C_{\rm comb}\left[1 + 2v^{\rm eff}_{2,2}\cos(2\Delta\phi)\right] + C_{\rm corr}(\Delta\phi)$$

$$C_{\rm corr}(\Delta\phi) = \frac{C^{\rm max}_{\rm corr}\,\Gamma^2}{(\Delta\phi - \pi)^2 + \Gamma^2}$$

Combinatoric modulation including flow contribution

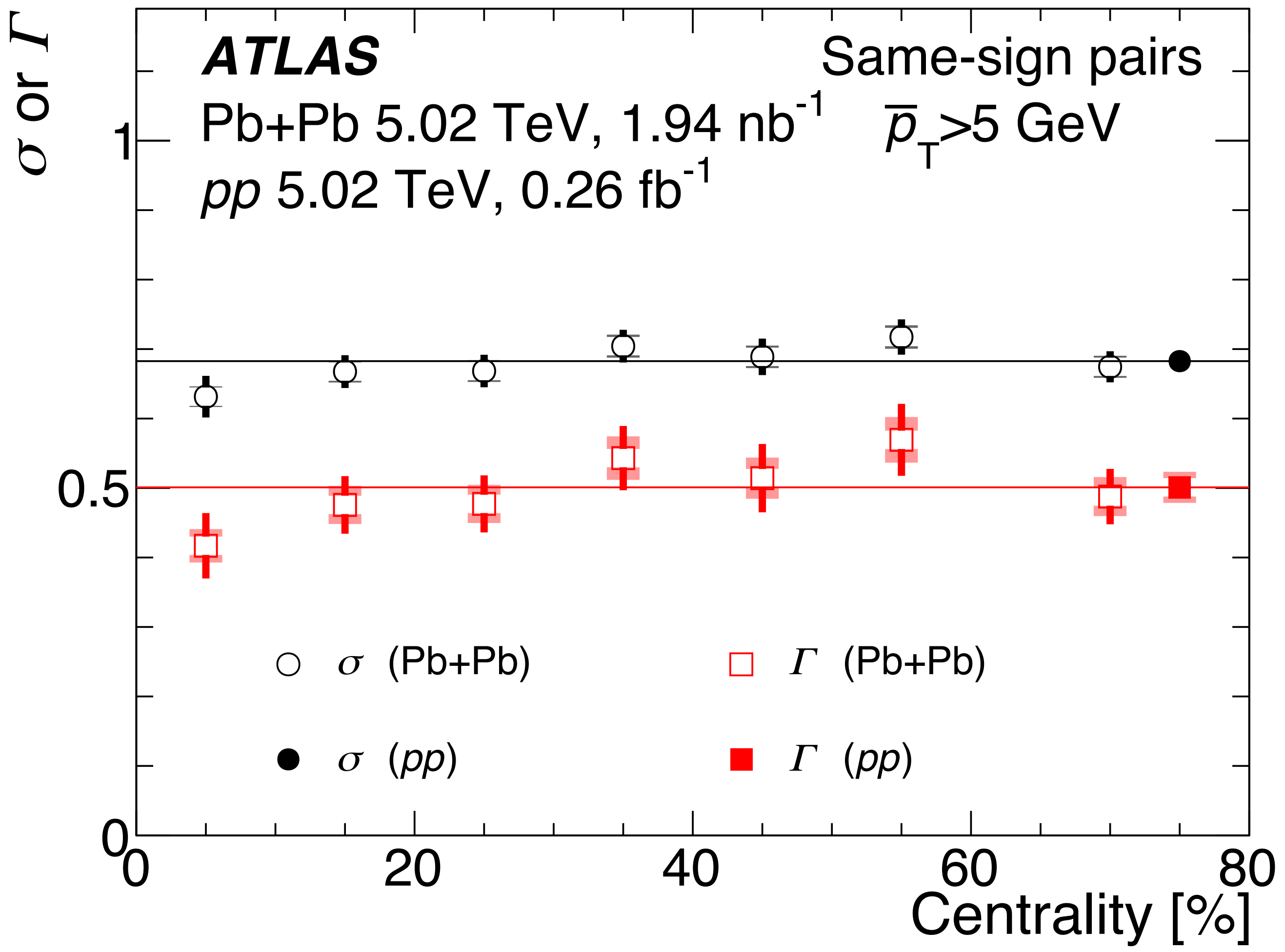
Back-to-back HF correlation

$$\sigma \equiv \sqrt{\int (\Delta\phi - \pi)^2\left(C_{\rm corr}(\Delta\phi) - C_{\rm corr}(0)\right) {\rm d}\Delta\phi}$$

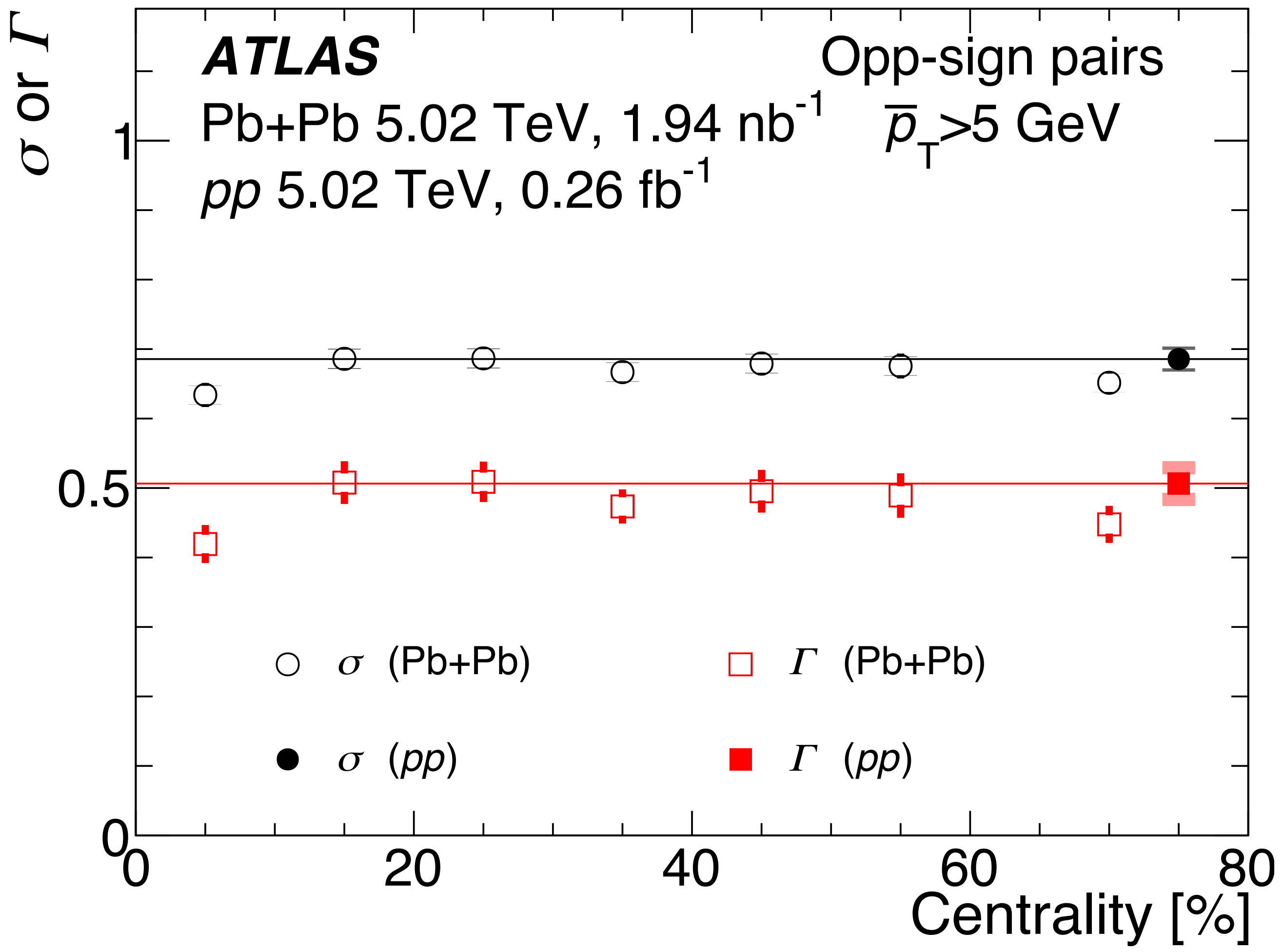
HF pair azimuthal correlation — width

[PRL 132 (2024) 202301]

Same-sign muon pair
($b\bar{b} \rightarrow \mu^{\pm}\mu^{\pm}$)



Opposite-sign muon pair
$c\bar{c}/b\bar{b} \rightarrow \mu^{\pm}\mu^{\mp}$



Central Pb+Pb collisions

Peripheral Pb+Pb collisions

- 0-10% most central collision is found to have narrower correlations
- Narrower $\Delta\phi$ correlation width → larger radiative contribution in energy loss

Summary

- Some of the most recent results in heavy flavor physics by ATLAS was presented
- Provide inputs and constraints to various QCD calculations in flavor physics and QGP physics
- New measurements using the full Run1 + Run2 statistics and Run3 data ongoing: stay tuned!

ขอบคุณ

All **B physics** results from ATLAS:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

All **Heavy Ion physics** results from ATLAS:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults